Full Fill Algorithm for CNG

Presentation to

Natural Gas Vehicle Technology Forum

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Objective — Improve Filling of NGVs

- Customers and employees noted:
  - differences between gauge and dispenser
  - lower driving ranges than expected
- Early changes improved fills, but vehicles still not completely full
- Experimental approach was needed to identify a better method

Background

Fueling Process
Vehicle Storage Cylinders

Natural Gas Is Compressible

- Natural gas follows Compressible Gas Law

$$P\ V = Z\ n\ R\ T$$

- Storing more gas (increasing *n*) in a fixed volume (*V*) at the same temperature (*T*) results in higher pressure (*P*)

  – R -- Ideal Gas Constant   Z -- compressibility factor

Gasoline Fueling Is Familiar

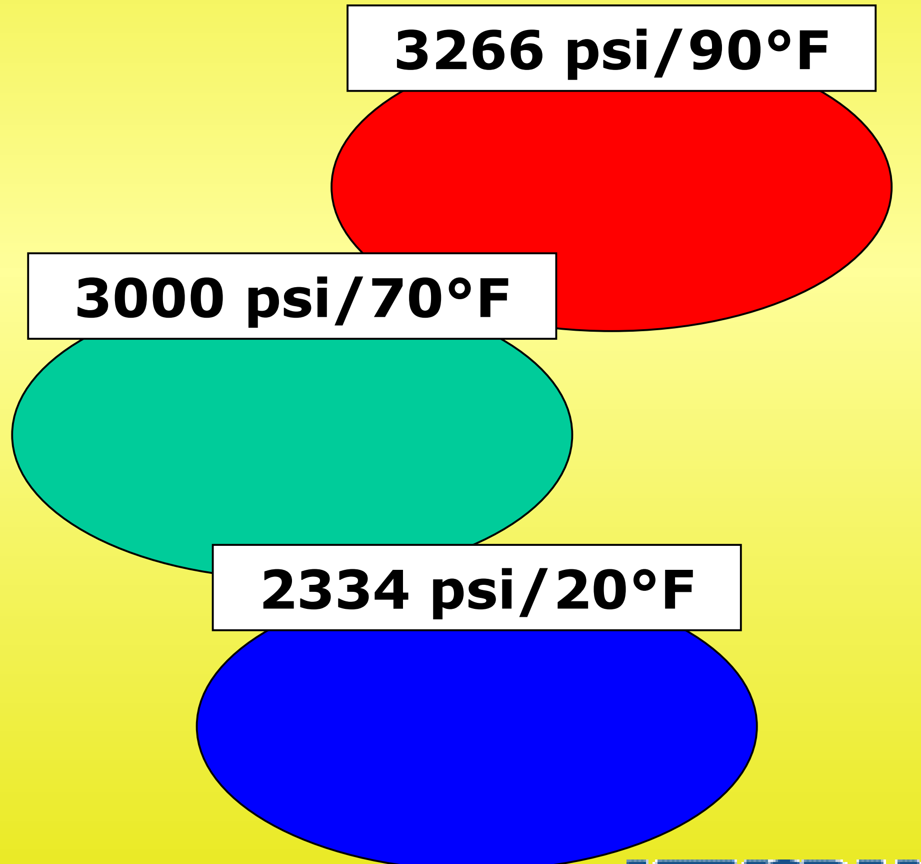
- Gasoline fills tank by displacing air
  - Like water in a glass
- More gasoline takes up more room in tank (less air)
- Gasoline is moved by a pump

NG Fueling Differs

- Natural gas occupies entire volume
  - Like air in a balloon or a tire
- More natural gas increases either:
  - Volume (with little pressure change, as in a balloon), or
  - Pressure (with little volume change, as in a tire, or a natural gas cylinder) — NGVs store gas by increasing pressure
- Natural gas moves due to pressure difference, from higher to lower

Pressure Changes With Temperature

- **If the volume and the amount are the same, hotter gas has a higher pressure than colder gas**

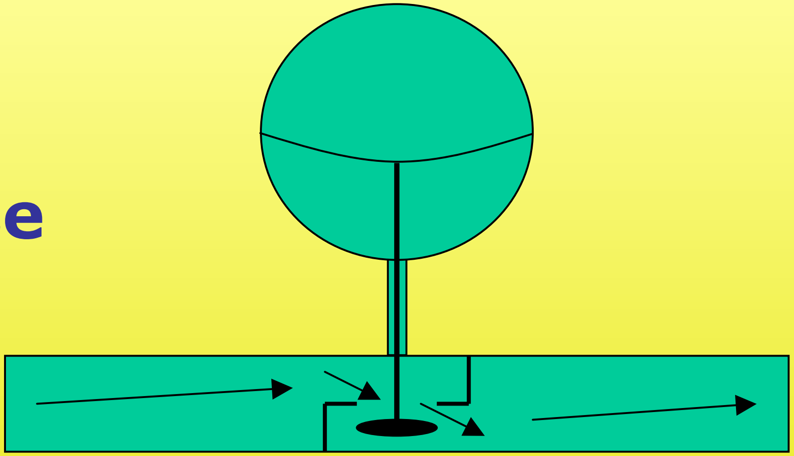


Cylinder Design

- Natural gas cylinders are designed to be full at a given pressure when the gas and cylinder are at a given temperature, e.g., 3000 psi @ 70°F
- Cylinders must be filled to lower pressures when cold
  - Moving to a warm garage should not cause pressure to increase above capability of cylinder to safely store it

First Approach In Industry

- Dome load valves provided ambient temperature-varying target pressure for fueling
- Pressure of gas contained in dome varied based on ambient temperature
- Higher pressure in dome flexed metal diaphragm to open valve
- When pressure in fill hose reached the same value, diaphragm moved in and closed valve



Next, Electronics Took Over Control Function

- **Electronic controls *(Programmable Logic Controller-PLC)* first mimicked dome loads**
  - **Read air temperature**
  - **Compute temperature-compensated fill pressure**
  - **Read pressure in line while filling**
- **Electronics reduced problems**
  - **Domes would leak, components wear**

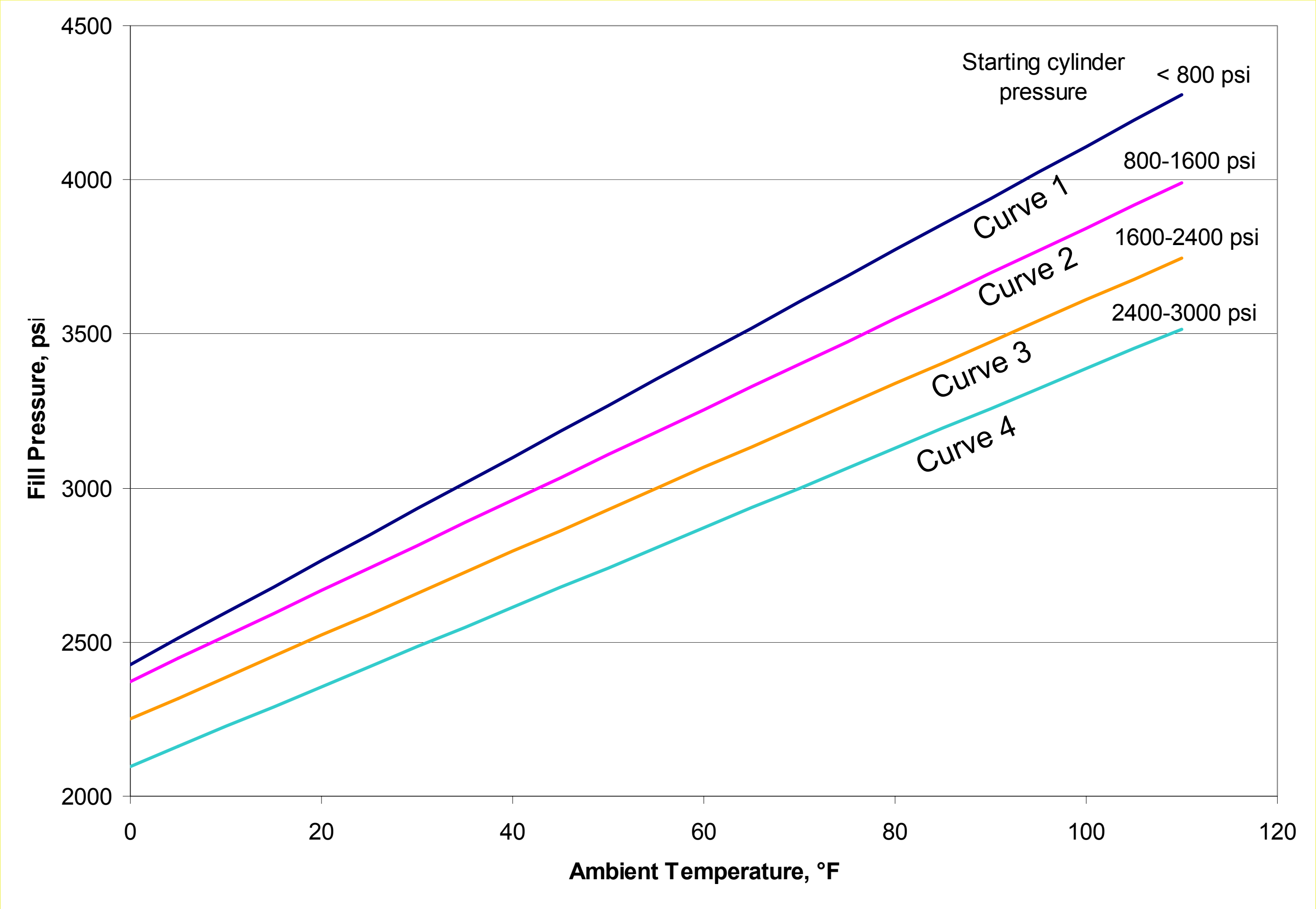
Fast Fill Heating Effect

- The fueling process compresses gas in a tank, causing it to occupy less space, raising temperature
  - Same effect causes air compressors, bike tire pumps to warm up
  - Opposite effect of reducing pressure causes cooling, e.g., using *Dust-Off* compressed air

Compensating Controls

- **The next step in PLC programs:**
  - **Adjusted target values based on starting conditions (temperature and pressure in cylinder) *(Wilson)***
  - **Computed thermodynamics and dynamics of fueling process to compensate for temperature rise *(Accufill—IGT/GRI)***

Original Wilson Algorithm — Fill Target Pressure Shifted By Start Pressure



Problems With Both Techniques

- The Wilson method approached complete fills closer than dome load valves, but people believed systems could do better
- *Accufill* accurately models filling process, but requires more computing power than many dispenser controllers can provide

KeySpan's First Attempt To Improve Fill Level

- KeySpan experiments indicated Wilson's method was conservative
- Curves were modified to increase target pressure, provided more complete filling (fill curves 2 & 3 were eliminated)
- Resulted in improvement in fill level

Cylinder Types Vary

- Different construction methods
  - Type 1 -- All-metal cylinder made of steel or aluminum.
  - Type 2 -- A cylinder with a metal liner made of steel or aluminum and hoop-wound overwrap.
  - Type 3 -- A cylinder with a thin metal liner and fully wound overwrap.
  - Type 4 -- Similar to Type 3 with a liner made of nonmetallic material.

Type Influence

- All metal cylinders have more thermal mass, better heat transfer through them to air
- Any wrap acts as insulation layer between tank and air
- Plastic liner acts as a second layer of insulation, between gas and wrap, with less thermal mass

Size Influence

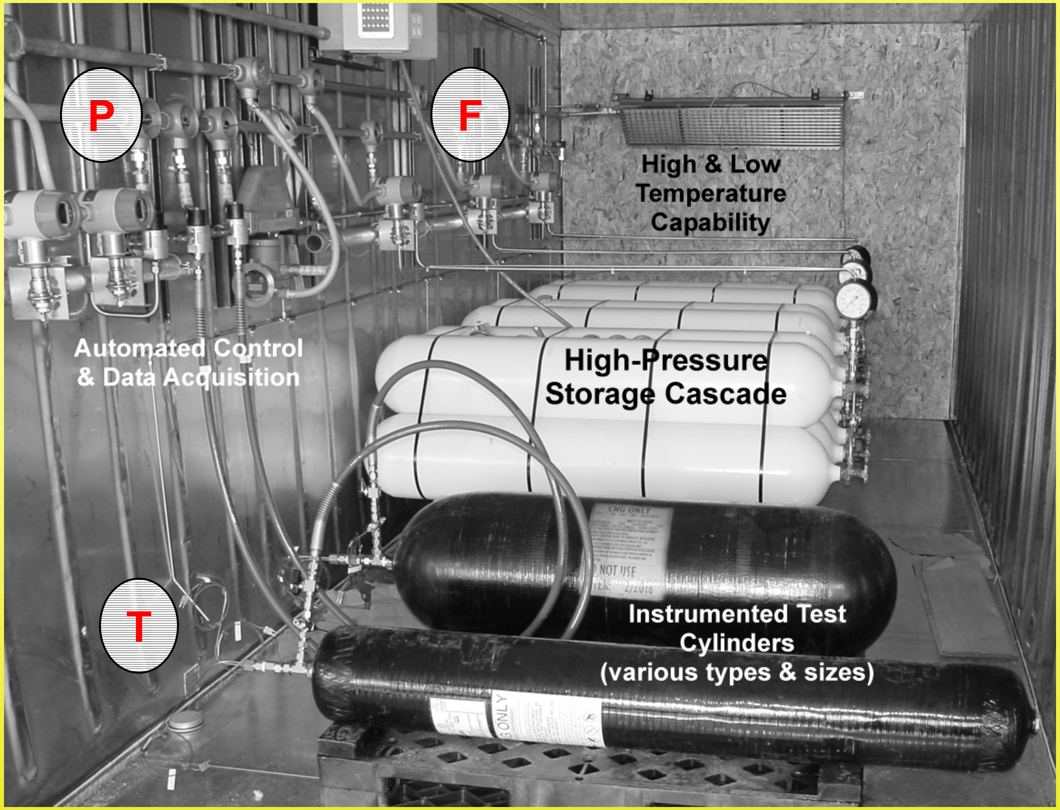
- It was thought that different cylinder sizes may affect fill levels:
  - Smaller cylinders have a higher exposed surface area to volume ratio, so that more heat would be transferred for each cubic foot of natural gas
  - Larger cylinders have more surface area and be able to transfer more heat
- Both may affect the fast fill heating effect by cooling gas during fill

Project Approach

To accumulate test data from filling different sizes and types of cylinders with different starting pressures at three different temperatures (20, 55, 90°F) in an environmental chamber

Controlled Environment For Testing

- Put storage, controls, vehicle cylinder in temperature-controlled space
  - Thermo-couples (T)
  - Pressure transmitters (P)
  - Mass flow meter (F)



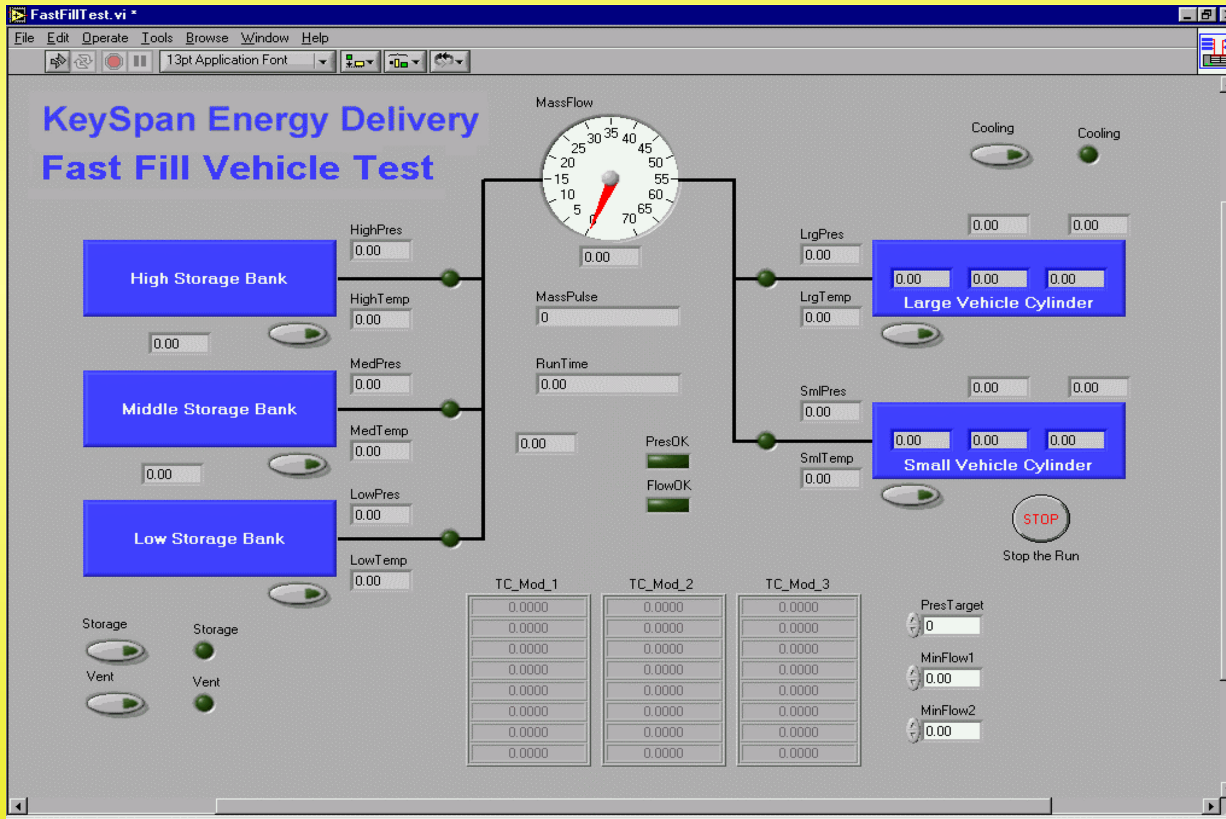
Cylinder Types/Sizes

- Type 1, 2, and 4 included
  - Type 3 not included because it is between Type 2 (due to metal liner), and Type 4 (due to complete wrap)
- Small and large sizes identified
  - 3-5 gallon gasoline equivalent
  - 8-12 gallon gasoline equivalent
  - Range used to accommodate manufacturer variations

Track Fueling Process

LabView 6*i* software

- **Monitor and control fueling process to simulate station, acquire and store data**



Determine Closeness To Full Fill

- Track pressure and temperature changes at 15 minute intervals as cylinders cool
- Determine pressure when gas returns to ambient target temperature (settled pressure)

Convert Observations To Procedure

- Analyze data to determine patterns
- Attempt curve fits to model results
- Compare with prior results

Temperatures Selected

- The range needed to cover most of the range experienced in New York
  - Extrapolation to hotter and colder conditions is possible
- Points selected to identify variations from linear relationship
- Values: 20°F, 55°F, 90°F

Pressure Ranges

- Pressures determined by KeySpan station configurations
  - 3600 psi station, 3000 psi vehicle
- Starting pressures cover
  - Empty and partially-filled vehicles
  - Full and partially-depleted station
- Additional tests for 4500 psi station, 3600 psi vehicle

Test Results

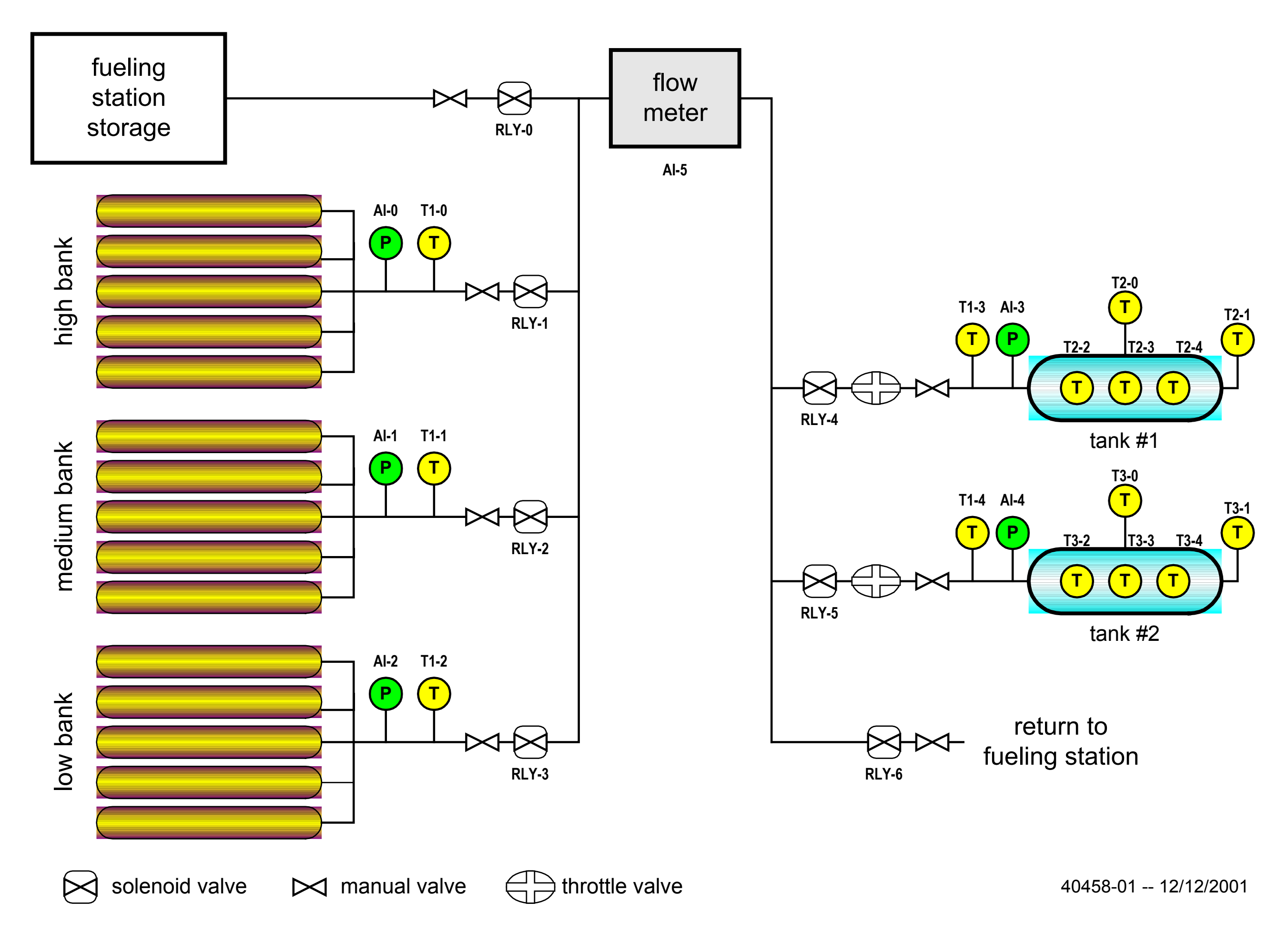
- 2 cylinder sizes
- 3 cylinder types
- 3 ambient temperatures
- 4+ starting pressure combinations

  ⇨ 80 tests

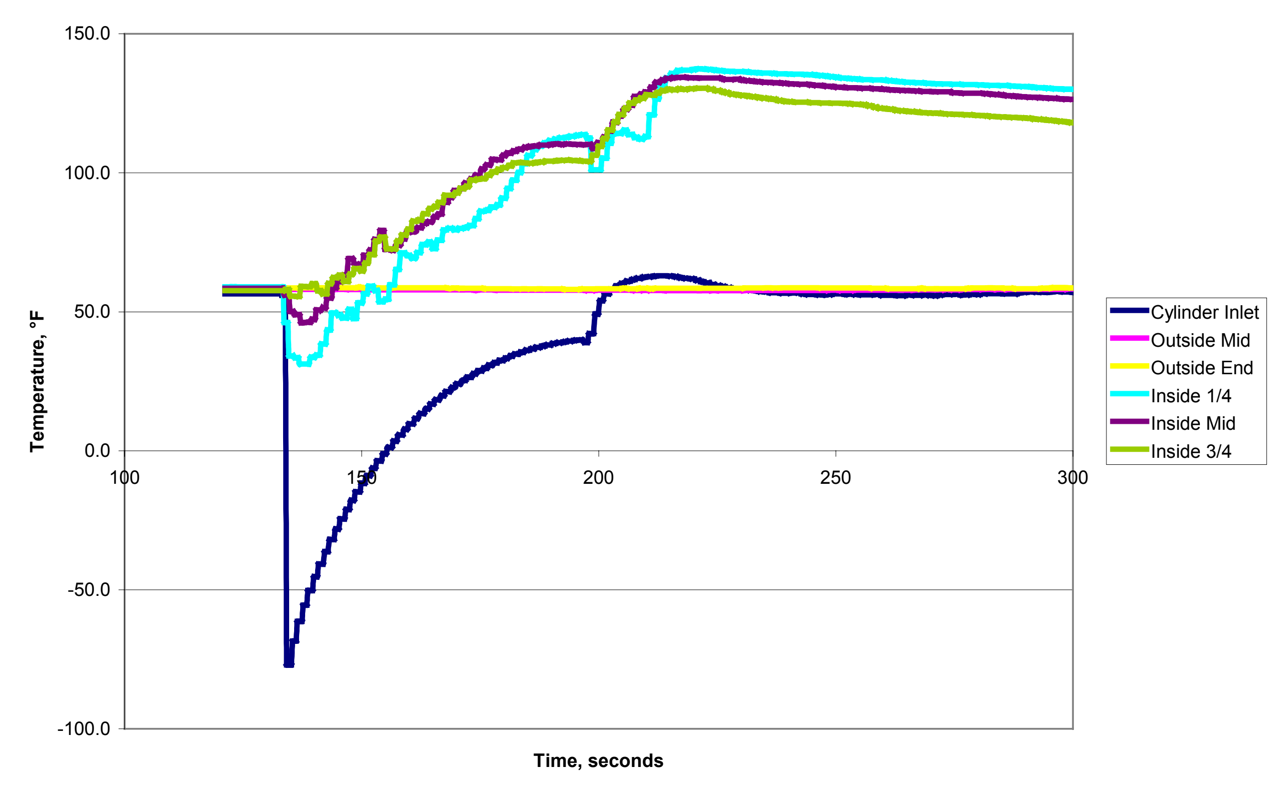
Data Collected

- Temperature, pressure at start
  - Low bank station cascade
  - Mid bank station cascade
  - High bank station cascade
  - Vehicle cylinder (inlet, internal, skin)
- Temp, pres, and mass flow during fueling
- Temp, pres during cooling

Monitored Points



Test Details
Fueling Process



A sample Type 4 cylinder test

Analysis

Determine Final Pressure

- STRAPP (natural gas properties calculator) from National Institute of Standards and Technology (NIST) used to determine pressure when cooled to ambient
- End of fill and cooling points used to determine amount of gas in cylinder (density)
- Gas pressure for ambient temp and density computed

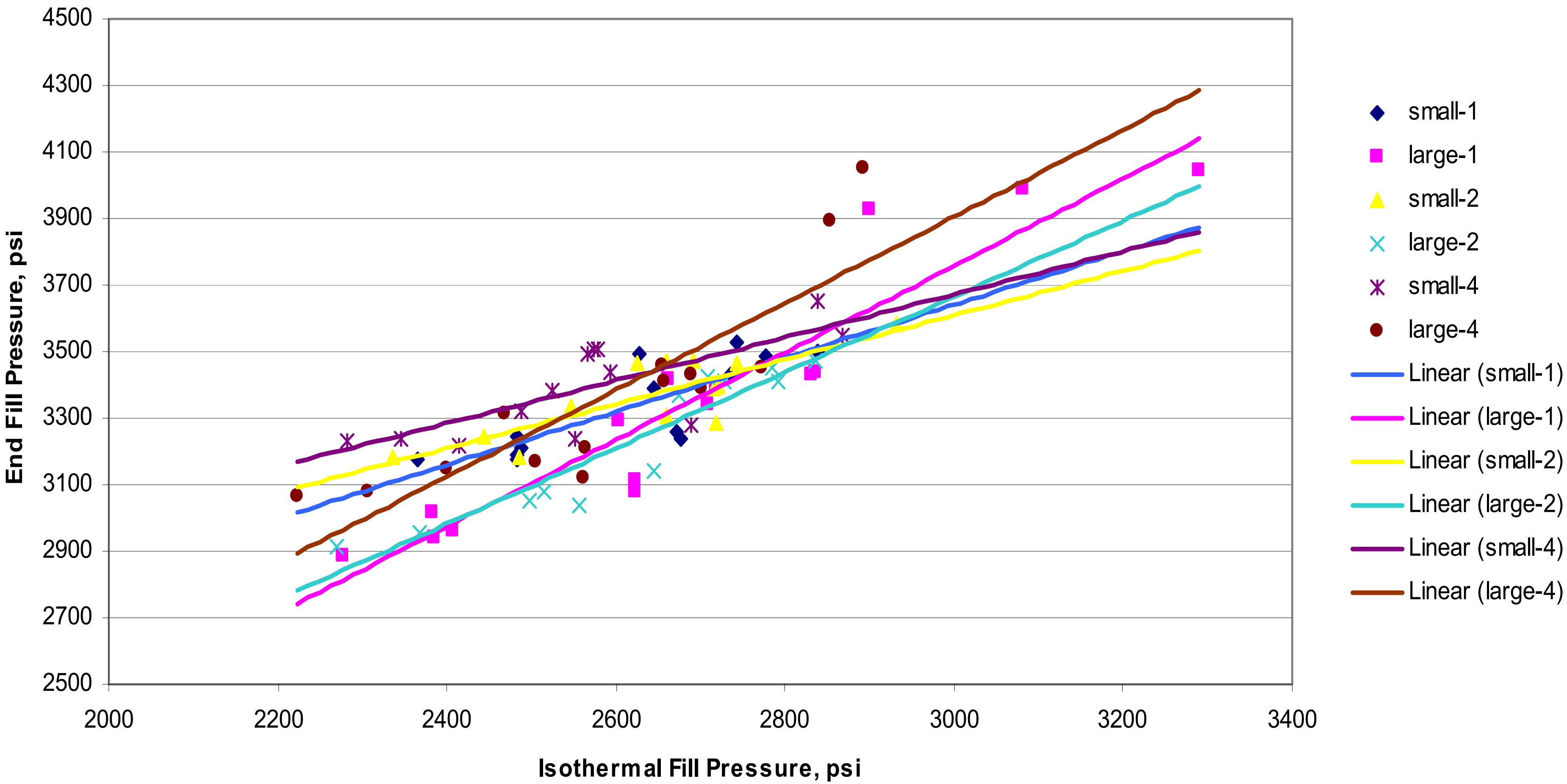
Definitions

- **Fill Pressure ⇨ pressure of gas when last valve is closed**
- **Isothermal Pressure ⇨ pressure of gas cooled to ambient temperature**
- **Fill Pressure Difference ⇨ fill pressure - starting pressure**
- **Isothermal Pressure Difference ⇨ isothermal pressure - starting pressure**

Comparing End-of-fill Pressure With Isothermal (Target) Pressure Works Poorly

- Simple comparison between pressure when fueling stopped with pressure when temperature returned to ambient does not work very well

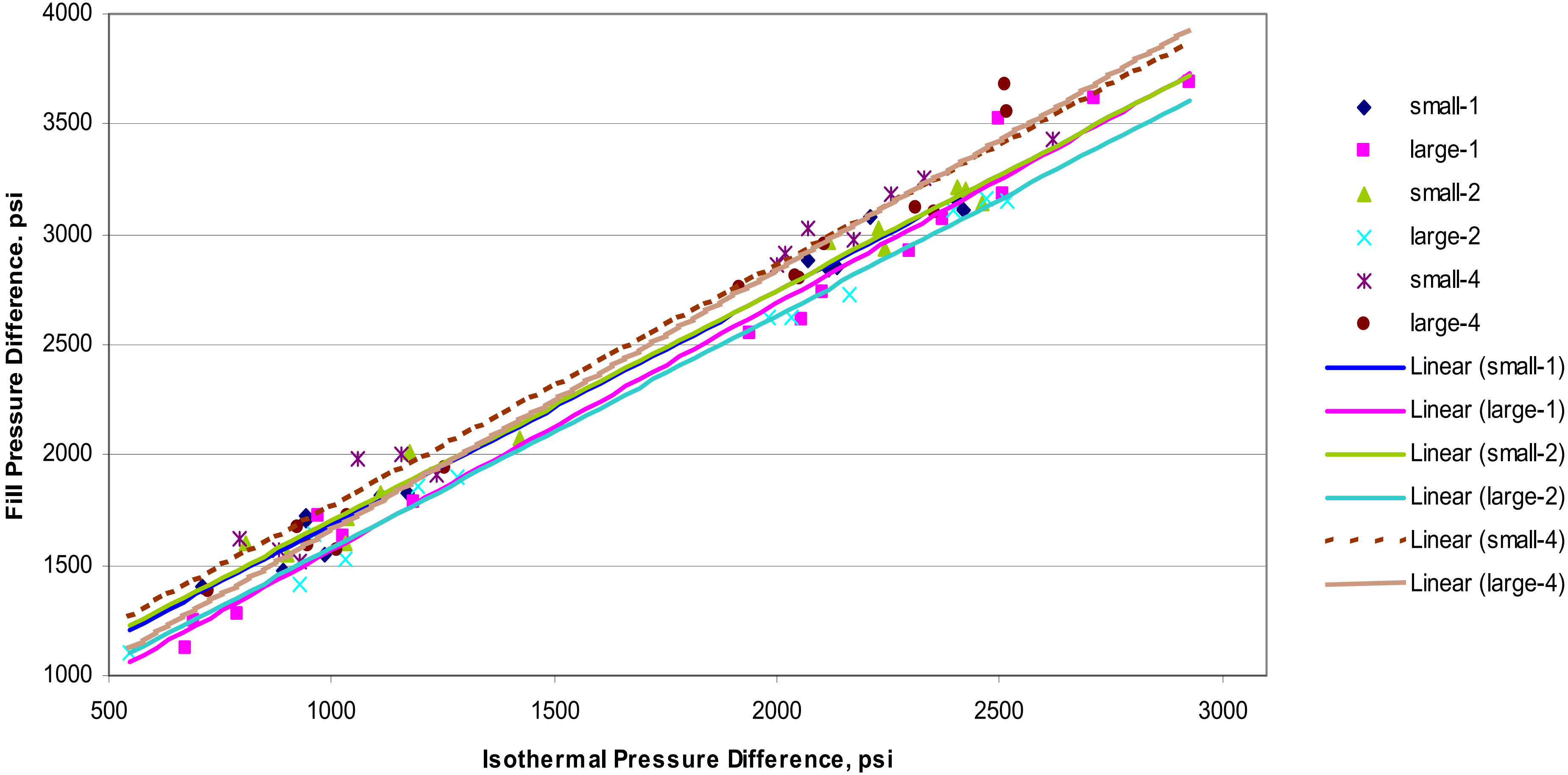
Simple Relationship Doesn't Work



Comparing Pressure Differences Is Better

- The correlation is better between observed increase in pressure *(Fill Pressure Difference)* and desired increase in pressure *(Isothermal Pressure Difference)*

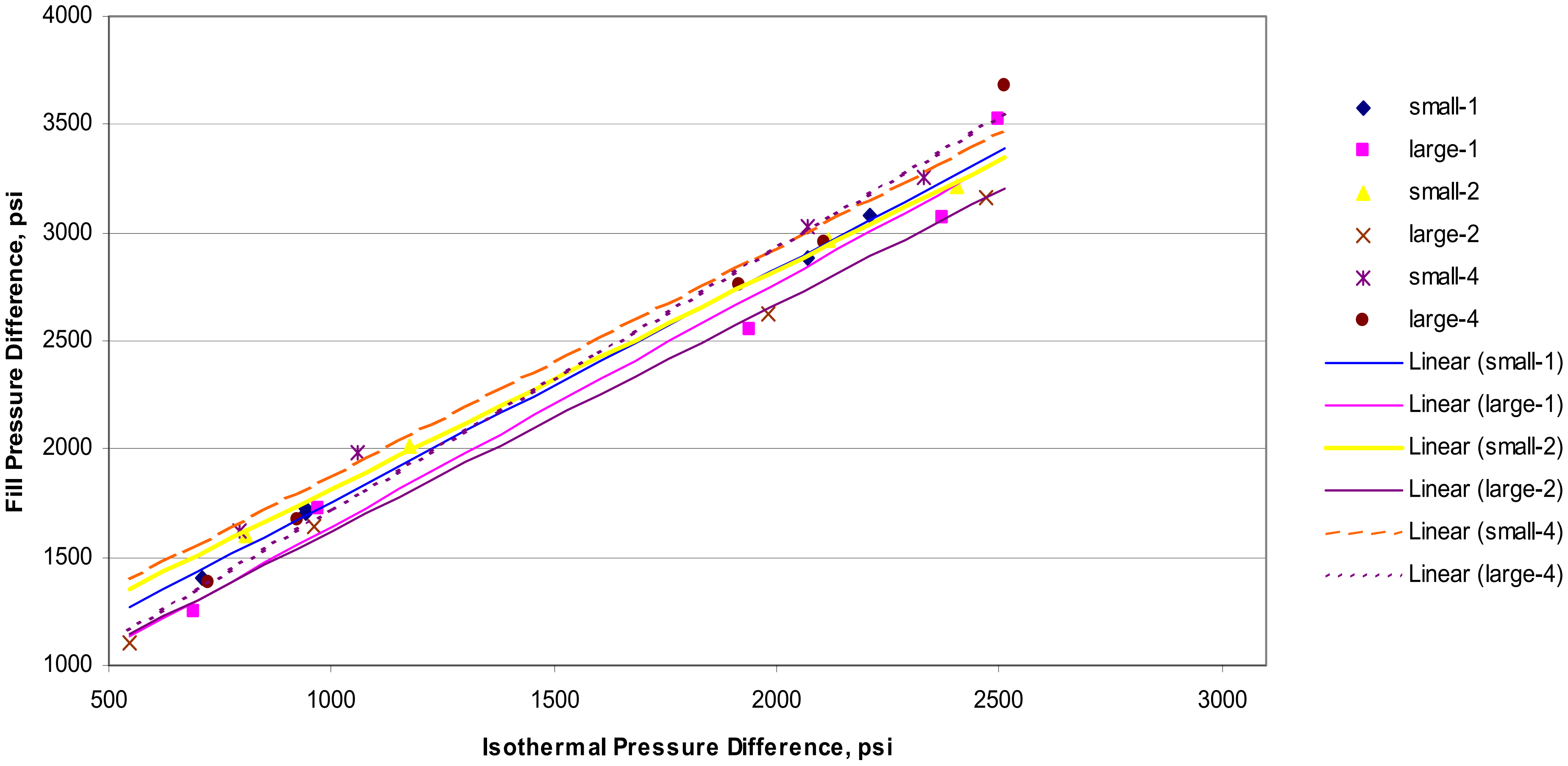
Pressure Differences Correlate Better



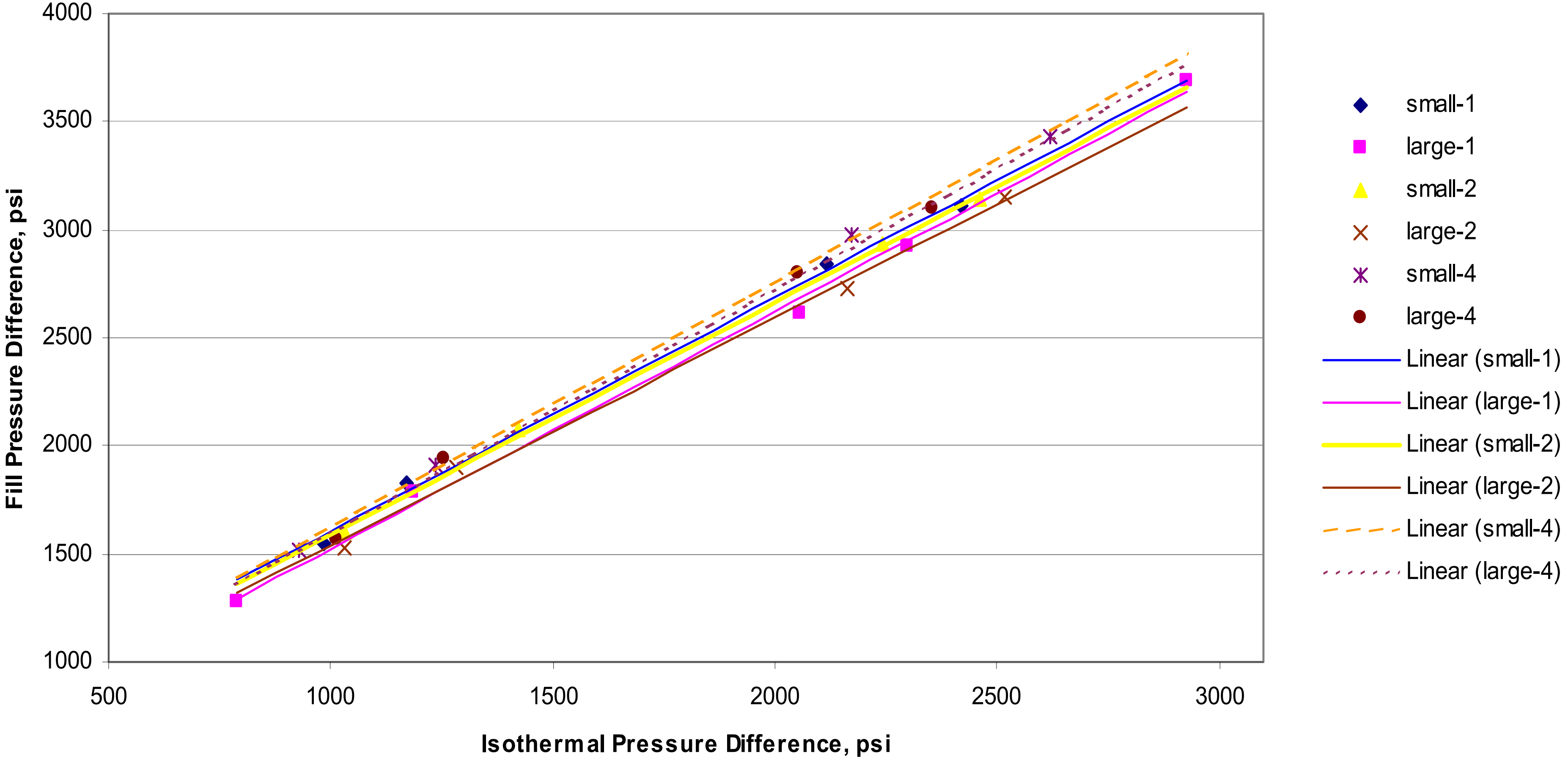
Effect Of Temperature On Pressure Differences Is Small

- Comparison between pressure differences produces similar results for different temperatures
- Minor differences shift fill pressure difference by < 2 psi/°F

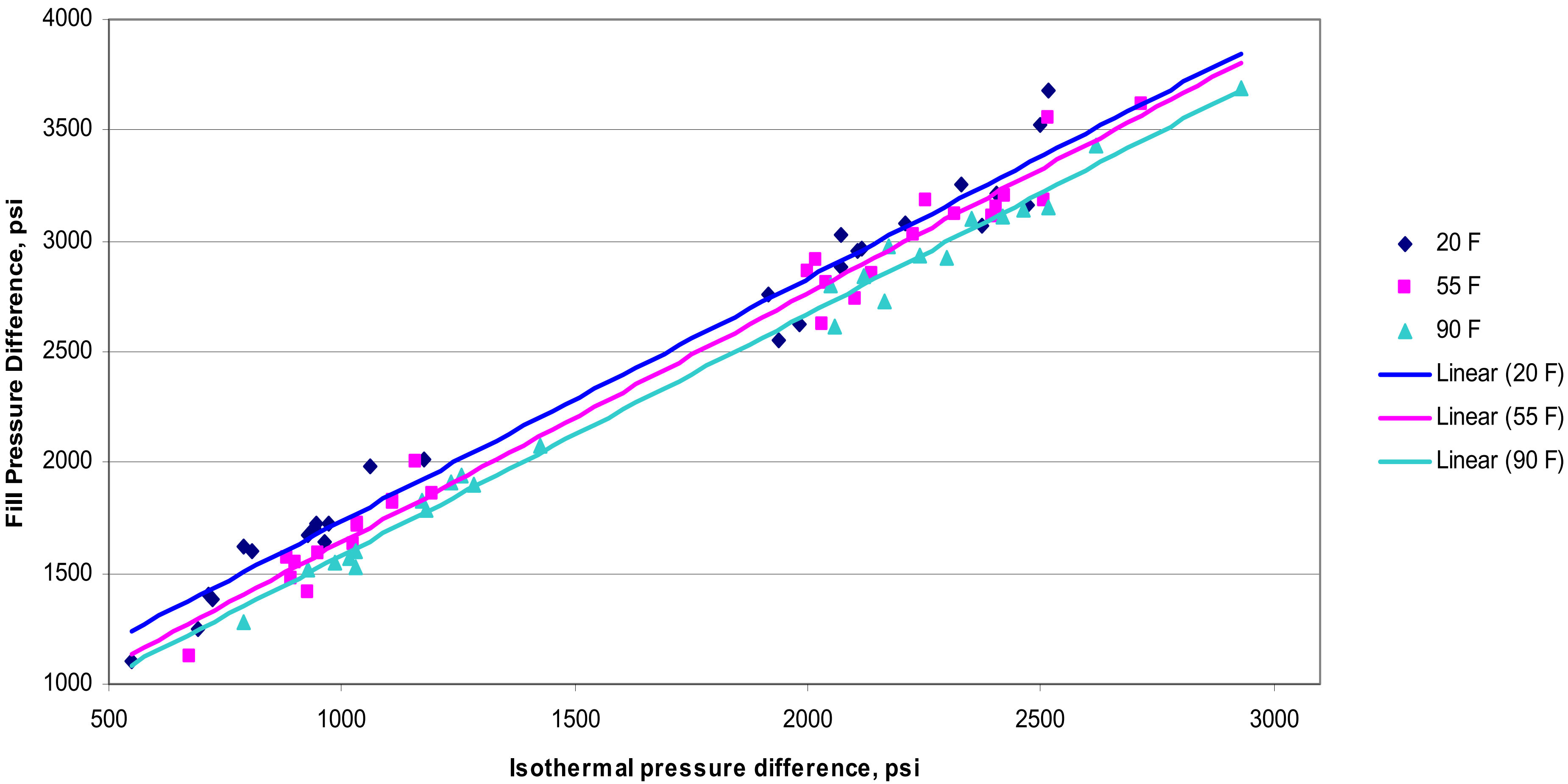
Works At Low Temp, 20°F



And At High Temp, 90°F



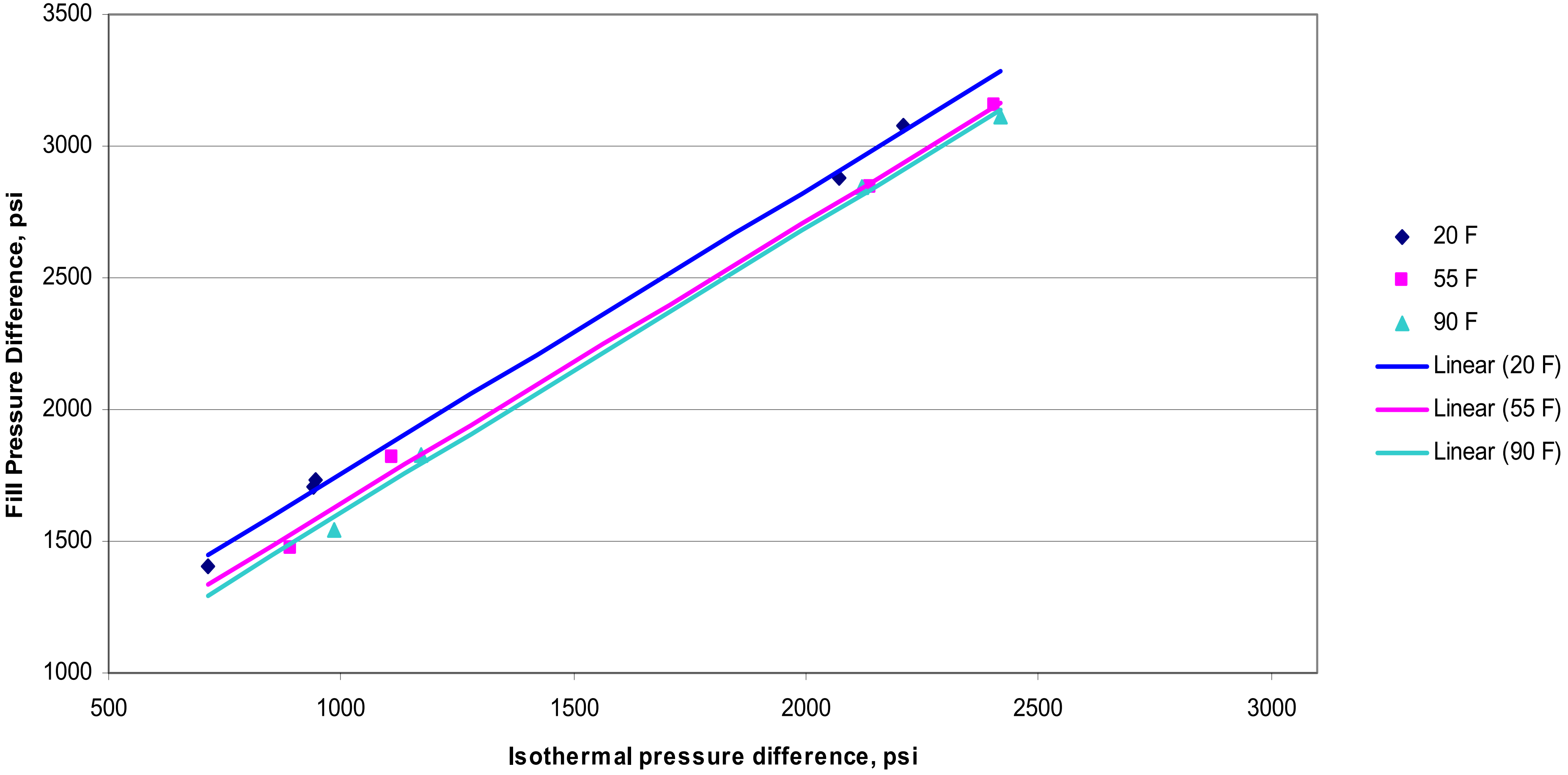
Minor Temperature Dependence



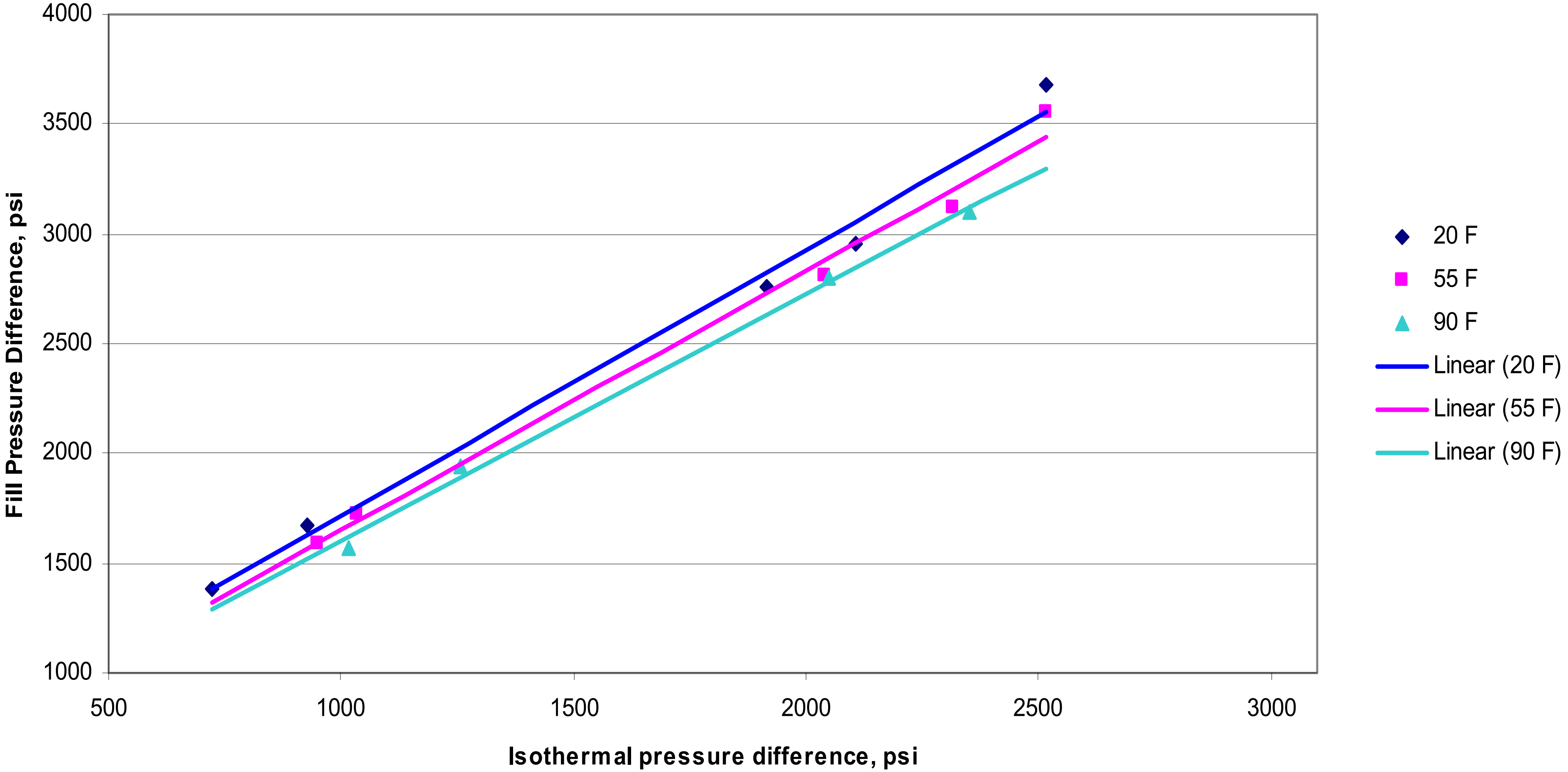
Pressure Differences Not Affected By Cylinder Type And Size

- Correlation produces similar results independent of cylinder type or size
- Minor temperature effect demonstrated for each cylinder

Works for Small Type 1 Cylinder



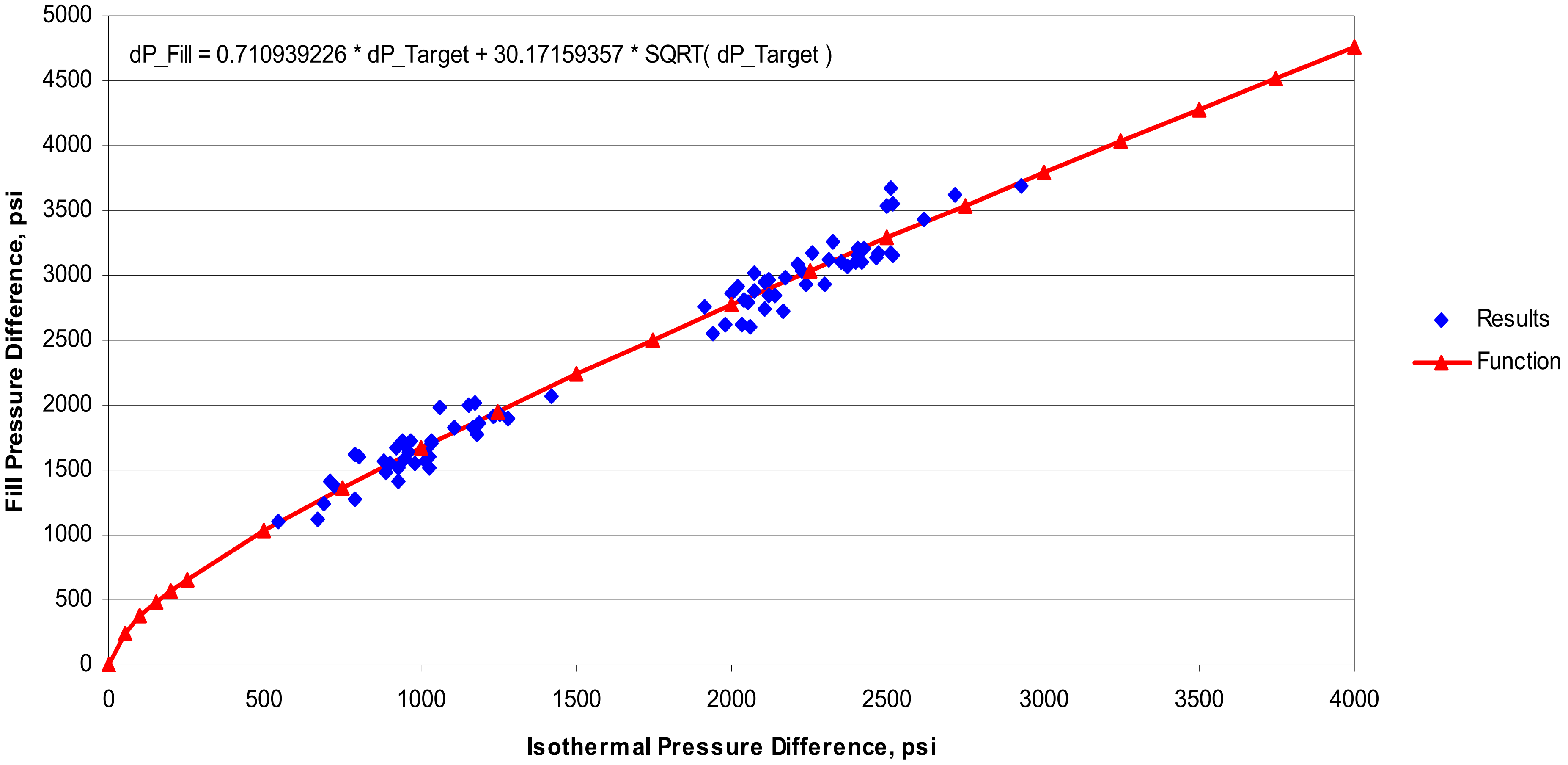
Through Large Type 4 Cylinder



Function Accurately Describes Relationship

- Comparison included linear, first-, second-, and third-order polynomial, and power equations
- Curve fit using linear + square root developed acceptable equation

Simple Curve Fit Is Good Approximation



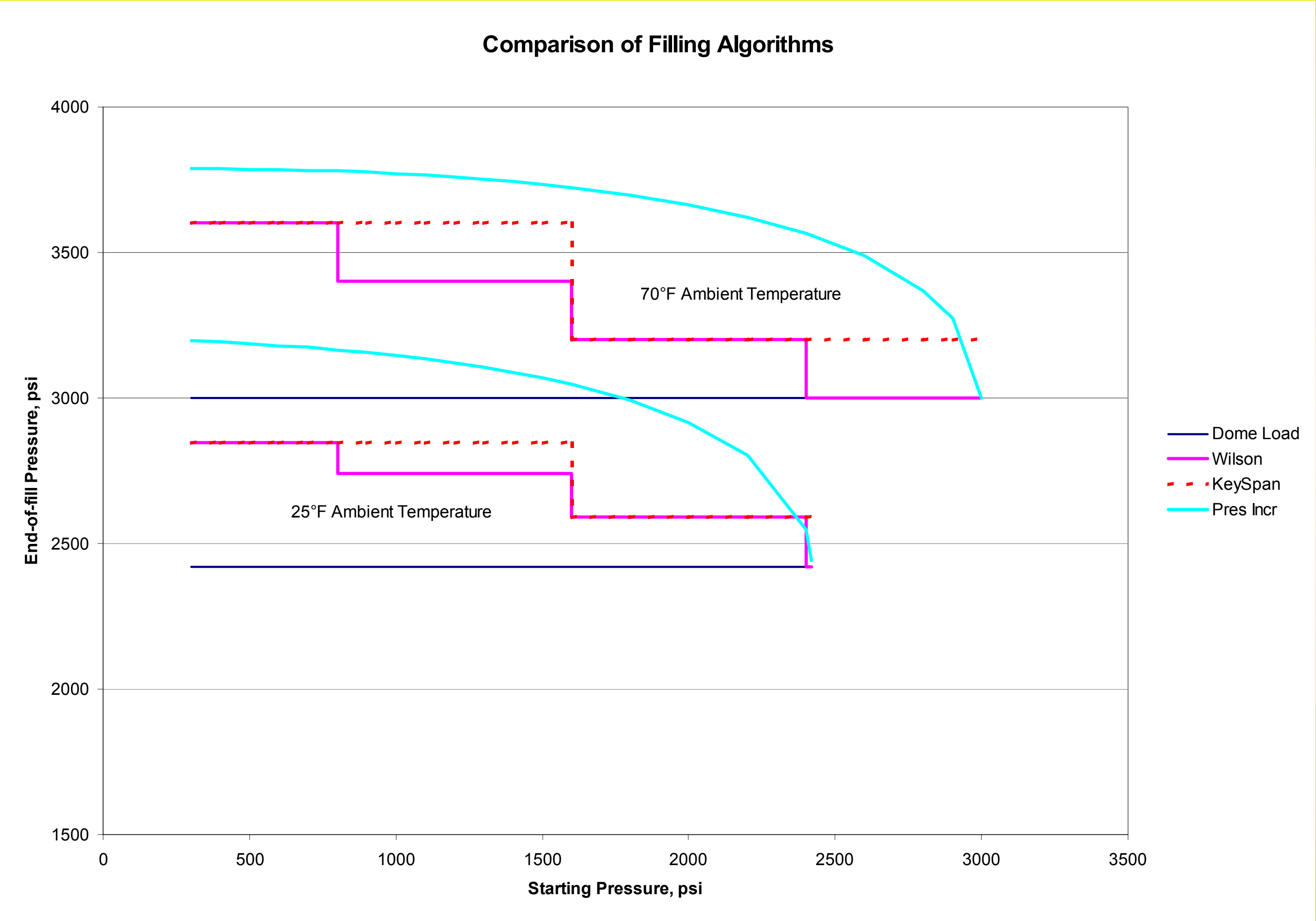
Filling Example

- Starting conditions: 40°F, 350 psi
- Isothermal pressure: 2613 psi
- Iso. pres. difference: 2263 (= 2613 - 350)
- Fill pres. difference: 3044 (from formula)
- Fill pres. target: 3394 (= 3044 + 350)

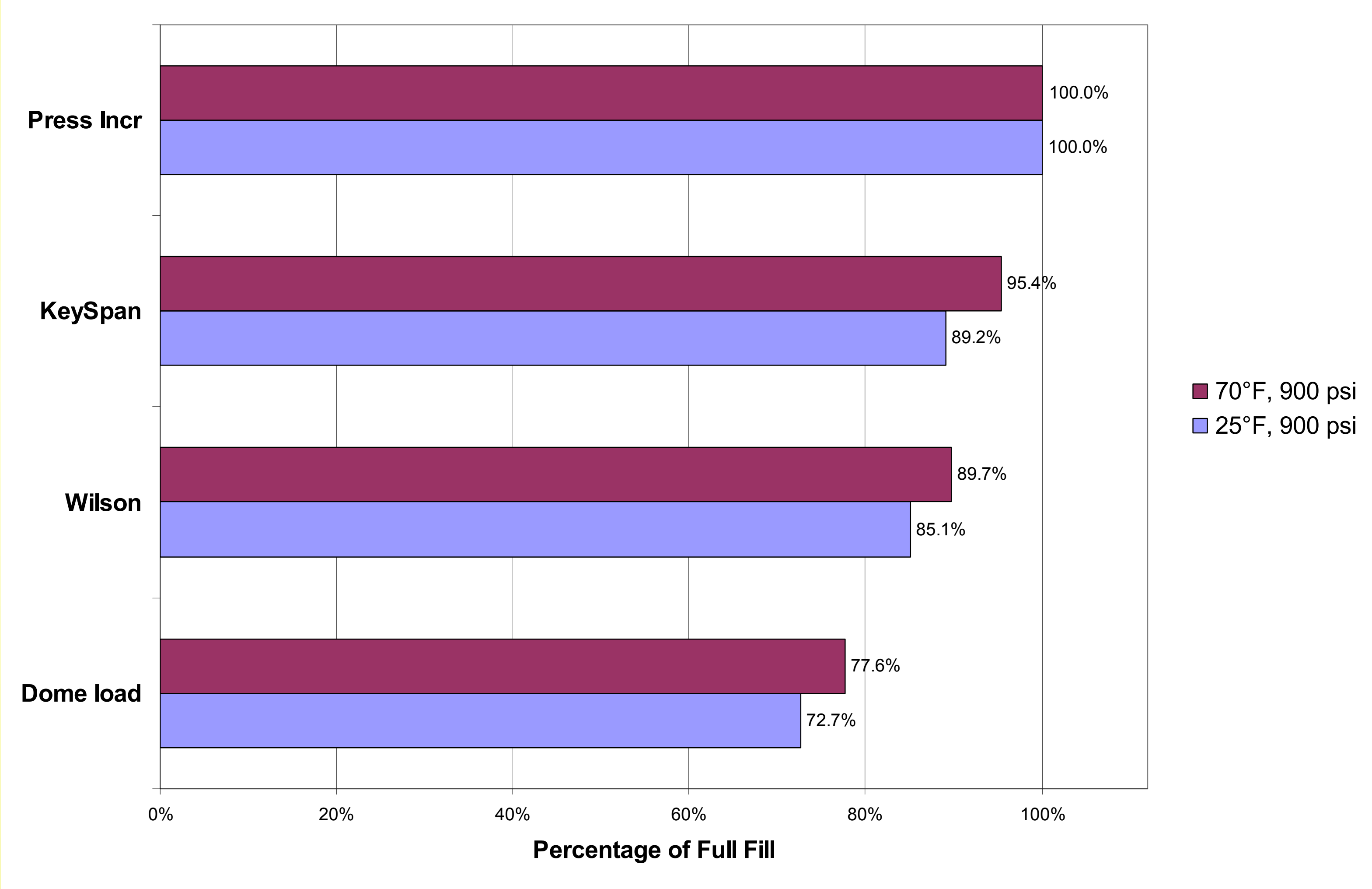
Comparison Of Pressure Differences

- Determining pressure increase at end of fill based on desired temperature-compensated pressure increase appears to work
- Process does not depend on knowing cylinder type or size
- Fine-tuning based on ambient temperature is possible

Filling Improved Over Time



Pressure Difference Method Meets Full Fill At Any Temperature*



* unless limited by safety considerations

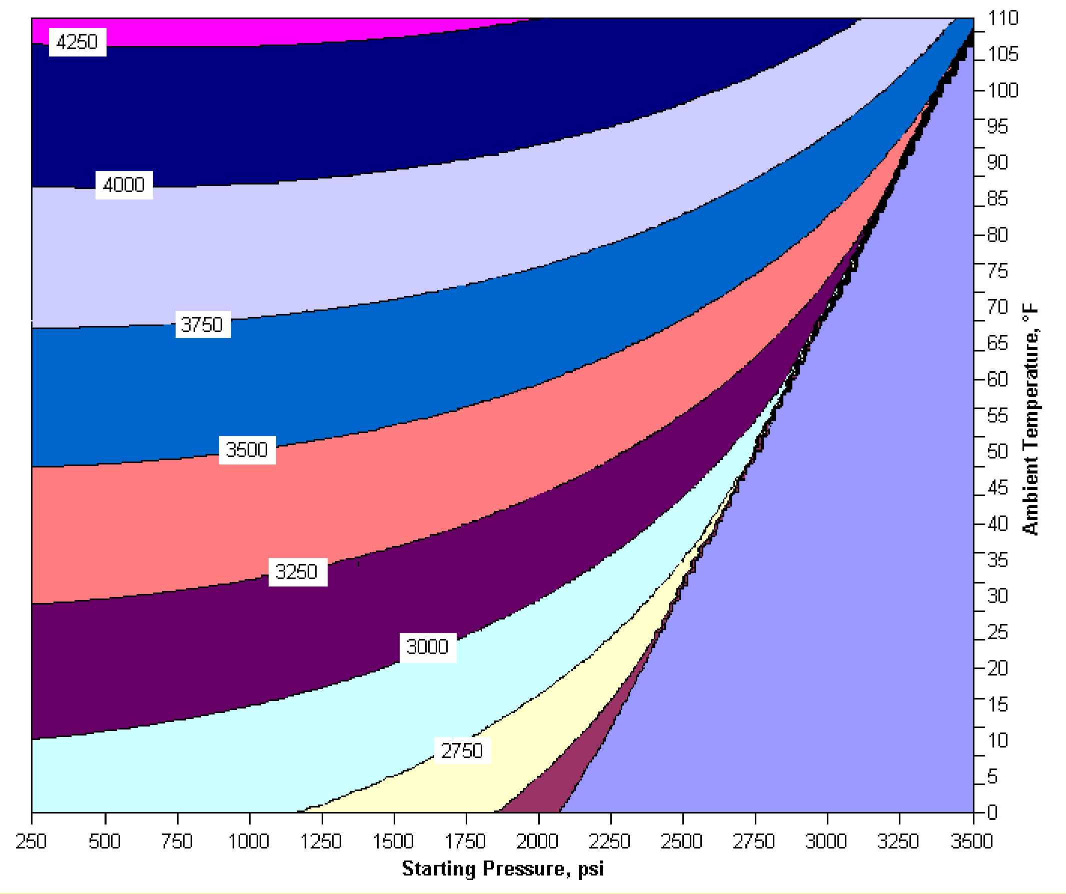
Safety Limits Recognized

- Temperatures during testing didn't exceed 200°F
- Maximum design pressure limits target pressure
  - Desired end-of-fill pressure should never be over 125% rated value, e.g., 3750 psi for 3000 psi cylinder

Station Equipment Limitations

- Maximum high bank station storage pressure: 3600 psi
- Minimum high bank station storage pressure: 3200-3400 psi *(before compressor starts)*
- Gas may be unavailable at pressure required to complete fill

End Pressures vs. Limits



Some T-P combinations can exceed safe limits (e.g., 3750 psi)

Recommendations

- **Implement method on PLC or other controller**
  1. **Measure ambient temp**
  2. **Determine desired target pressure**
  3. **Measure starting pressure**
  4. **Compute desired isothermal pressure increase**
  5. **Calculate fueling pressure increase**
     Fill press increase = 0.71094*Iso press increase + 30.17159*SQRT(Iso press increase)
  6. **Add fill pressure increase to starting pressure to determine final fill pressure**
- **Run vehicle tests to verify method**

Field Results Verified Algorithm

- Field tests of the new GTI/KeySpan fill algorithm conducted at the Hicksville CNG station. Tests included single tank and multi-tank vehicles.
- Tank capacity was calculated and compared to final fill pressures vs. actual volumes and expected volumes. Also compared were settled fill pressure at known temperature to the 70°F standard of 3000 psi. Results were ±1% of the desired 3000 psi at 70°F.

Vehicle Drivers Happy

- The drivers of the CNG vehicles filling at the station were also surveyed.
- The drivers noticed an increase in range. This permitted fill-ups every other day instead of every day.
- The volume of fuel delivered was consistent with vehicle gauge readings and what the drivers expected to consume.

Improvements Overall

- Good results were achieved, meeting the manufacturer's design tank capacity at 3000psi in Gasoline Gallon Equivalent.
- The results are consistent with graphs generated by GTI lab tests. The new algorithm on average is supplying 8% more fuel, and at times as much as 20% over the KeySpan modified algorithm.
- Recommendation was to expand the GTI/KeySpan algorithm to the other stations.

Conclusions

- Original design (e.g., dome load) did not meet expectations
- Previous changes came closer to achieving full filling
- Method using pressure increases is *successful*
- Implementation works independent of tank size, number, or type
- Limitations due to equipment and safety constraints